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Origin and evolution of Yakutian diamonds:

Constraints on sources and timing from a combined petrological
and geochemical study of diamonds and their inclusions

Daphne Wiggers de Vries

VRIJE UNIVERSITEIT

ORIGIN AND EVOLUTION OF YAKUTIAN DIAMONDS:
CONSTRAINTS ON SOURCES AND TIMING FROM
A COMBINED PETROLOGICAL AND GEOCHEMICAL
STUDY OF DIAMONDS AND THEIR INCLUSIONS

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Origin and evolution of Yakutian diamonds: Constraints on sources and timing from a combined petrological and geochemical study of diamonds and their inclusions (*Translated title: Oorsprong en geschiedenis van Jakoetische diamanten: Inzicht in herkomst en ouderdom door gecombineerd petrologisch en geochemisch onderzoek naar diamanten en hun insluitels*).

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Voor mama

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SUMMARY / SAMENVATTING

Summary

Diamonds are not only beautiful gemstones. Diamond's hardness allows it to withstand almost every physical and chemical form of destruction, for example erosion at the Earth's surface and transport in a kimberlitic magma. Some diamonds are reported to be almost as old as the age of the Earth. Consequently, the evolution of the Early Earth can be studied through diamonds, as well as the processes that are important for the evolution of the lithosphere. Due to recent advancements in analytical techniques, especially techniques that allow in-situ analyses of small amounts of material, it is possible to study the growth conditions of *single* diamonds in great detail in order to understand the processes that control their origin and formation history.

In this thesis, diamond crystals from Yakutia (Russia) containing mineral inclusions were subjected to multiple high precision, high spatial resolution techniques in order to determine their geochemical (major- and trace elements) and isotope composition. Their internal growth structure, as well as the position of their mineral inclusions, was examined in a crystallographic (cathodoluminescence) study. The internal structures reveal insight into the origin and growth history and allow us to study their formation history in great detail. The objectives of the research carried out in this thesis are to use modern high resolution techniques to resolve three highly debated topics; (1) What is the genetic origin of inclusions in diamonds? (2) What are the origins of carbon sources in the mantle? (3) What is the timescale of diamond growth?

The set up of a new micron-scale technique in this thesis (i.e., combination of electron backscatter diffraction and 3-D cathodoluminescence on a FIB-SEM instrument) allows us to provide quantitative criteria to help resolve the ongoing discussion about the genetic origin of mineral inclusions in diamonds. In other words, were inclusions formed *simultaneously* with the diamond host (syngenetic inclusion) and were they an *exact* record of the diamond's formation history? This combined technique involves sequential milling with a focused ion beam of micron-scale slices of diamond together with its mineral inclusions. The consecutive slices are studied with cathodoluminescence to determine the shape of the inclusion and the geometry of the diamond zonation around. The combined technique contributes to a better understanding of the complex growth histories of diamond and the micron-scale inter-relations between host diamond and inclusions.

The research in this thesis furthermore reveals that diamonds from the Mir, 23rd Party Congress and Udachnaya kimberlite pipes in Yakutia have different growth zones that formed from different source fluids. Mantle heterogeneity and Rayleigh type fractionation processes impose relatively small variations in carbon isotope composition ($-5 \pm 2\text{‰}$ $\delta^{13}\text{C}$) of the diamonds, an exception here is the 2 billion year old source at Mir from which diamonds with 'light' $\delta^{13}\text{C}$ values ($<-10\text{‰}$) precipitated. The very radiogenic initial Os isotope ratios of the sulphide inclusions (0.14 to 2.22 $^{187}\text{Os}/^{188}\text{Os}_i$) imply incorporation of radiogenic Os from subducted oceanic lithosphere, a conclusion that is also supported by the anomalously light carbon isotope compositions of some Mir diamonds. Subducted Archaean to Early Proterozoic lithosphere, mixed with the ambient mantle, is therefore considered to be a significant component in diamond formation beneath the Siberian Craton.

The research carried out in this thesis also demonstrates two major periods of Yakutian diamond formation; i.e., ~2.1-1.8 billion years (eclogitic and lherzolitic diamond populations) and ~1.0-0.9 billion years (eclogitic diamond populations). Both periods are associated with accretion of the Siberian Craton and subsequent melting and upwelling of metasomatic fluids within its cratonic lithosphere. Importantly, several single diamonds have protracted timescales of growth with significantly different ages associated with core and rim zones. Zoned single crystals from Mir and 23rd Party Congress crystallised over intervals that were up to ~1 billion years apart.

Samenvatting (Summary in Dutch)

Diamanten zijn niet alleen mooie edelstenen. Door hun extreme hardheid zijn ze opgewassen tegen de meeste destructieve processen op en/of in de aarde. Bijvoorbeeld tegen fysische processen zoals erosie aan het aardoppervlak en chemische processen zoals transport in een kimberliet magma in de diepe ondergrond. Sommige diamanten zijn bijna net zo oud als de aarde. Daardoor zijn ze uitermate geschikt om meer te weten te komen over de geschiedenis van de aarde, evenals de processen die van belang zijn voor de vorming en ontwikkeling van de lithosfeer. Door de ontwikkeling van zeer geavanceerde meettechnieken (bijvoorbeeld metingen op een micrometerschaal of aan onderzoeksmonsters die slechts 10^{-15} g wegen) is het tegenwoordig mogelijk om de ontstaansgeschiedenis van diamant tot in detail te bestuderen om zo de processen te begrijpen die van belang zijn voor de vorming en groei van diamanten.

In dit proefschrift zijn diamanten met mineraal insluitsels afkomstig uit Jakoetië (Siberië) onderzocht met verscheidene analysetechnieken die de geochemische samenstelling (hoofd- en sporen elementen) en isotoopverhouding met hoge precisie en hoge ruimtelijke resolutie kunnen bepalen. Aan de hand van een gedetailleerde kristallografische (kathodeluminescentie) studie is de groeistruktuur van de diamanten (en ook de locatie van de mineraal insluitsels) nauwkeurig in kaart gebracht. De interne structuren geven inzicht in de vorming en de groei van het kristal en maken het mogelijk de ontstaansgeschiedenis tot in detail te bestuderen. Het onderzoek in dit proefschrift richt zich op drie specifieke aspecten van diamantpetrogenese waarover tot op heden stevig debat is of waarover tot nu toe juist verbazingwekkend weinig bekend is: (1) Wat is de (relatieve) oorsprong en ouderdom van mineraal insluitsels in diamant? (2) Wat is de herkomst van koolstof in de aardmantel? (3) Hoeveel tijd neemt de groei van een diamant in beslag?

Een nieuwe techniek is ontwikkeld (Electron Backscatter Diffraction in combinatie met 3D-kathodeluminescentie op een FIB-SEM machine) om bij te dragen aan het voortgaande debat over de oorsprong (relatieve oorsprong en ouderdom) van mineraal insluitsels in diamanten, dat wil zeggen, zijn de insluitsels *gelijktijdig* ('syngenetisch') met diamant gevormd en hebben ze *exact* dezelfde geschiedenis ondergaan zodat de insluitsels gebruikt kunnen worden om de geschiedenis van de diamant zelf te achterhalen? Deze gecombineerde techniek maakt het mogelijk om met een ionenbundel micrometer dunne plakjes uit de diamant met zijn insluitsels te 'zagen'. Deze plakjes kunnen vervolgens bestudeerd worden met kathodeluminescentie om de inter-groeirelatie tussen beide in kaart te brengen. Nauwkeurige analyses van de kristallografische oriëntatie en groeistrukturen van de mineralen tonen aan dat

deze geïntegreerde en vernieuwende techniek positief bijdraagt aan de vraag naar de oorsprong van mineraal insluitsels in diamant en leidt tot een verbeterd inzicht in het ontstaan van de complexe groeistrukturen die voorkomen tussen de diamant en zijn mineraal insluitsels.

Dit proefschrift toont verder aan dat de diamanten van de Mir, 23rd Party Congress en Udachnaya kimberlietpijpen in Jakoetië verschillende groeizones hebben en dat deze zijn gevormd door kristallisatie uit verschillende vloeistofbronnen. Variatie in de chemische samenstelling van de lithosfeer en Rayleigh-type fractionatie processen hebben weinig effect op de koolstofisotoopsamenstelling ($-5 \pm 2\text{‰ } \delta^{13}\text{C}$) van de diamanten, met uitzondering van de twee miljard jaar oude vloeistofbron in Mir waaruit diamanten met 'lichte' koolstofisotoopsamenstelling ($< -10\text{‰ } \delta^{13}\text{C}$) gekristalliseerd zijn. De zeer radiogene initiële osmiumisotoopsamenstelling (0.14 tot 2.22 $^{187}\text{Os}/^{188}\text{Os}_i$) van sulfideninsluitsels suggereert een rol voor gesubduceerde oceanische lithosfeer, een conclusie die ondersteund wordt door de 'lichte' koolstofisotoopsamenstelling van enkele Mir diamanten. Gesubduceerde oceanische lithosfeer met een Archaeïsche-Proterozoïsche ouderdom is daarom, naast jongere niet-radiogene mantelvloeistoffen, een zeer belangrijke component voor de vorming van diamant onder het Siberische Craton.

Ten slotte laat dit onderzoek zien dat er twee belangrijke periodes van Jakoetische diamant vorming waren; namelijk, ~2.1-1.8 miljard jaar (eclogitische en lherzolitische diamant populaties) en ~1.0-0.9 miljard jaar (eclogitische diamant populaties). Beide perioden komen overeen met momenten van accretie van het Siberische Craton en het achtereenvolgens smelten en opwellen van vloeistoffen vanuit de lithosfeer. Enkele individuele diamanten kristalliseerden bovendien gedurende een geologisch lange tijd, omdat de verschillende groeizones geassocieerd zijn met verschillende ouderdommen. Deze diamanten van de Mir en 23rd Party Congress kimberliet zijn gevormd gedurende periodes tot één miljard jaar.